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Chiller/Tower Interaction

Take It to The Limit ...Or Just Halfway?

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Those involved in the HVAC industry have long studied the interaction of cooling towers and chillers. It is apparent that leaving-tower water temperature at any load and constant water flow is a function of the tower's design, fan speed and the amount of heat to be rejected, as well as the ambient wet-bulb temperature. It is also evident that the chiller requires less power as the water temperature leaving the tower (entering the chiller condenser) decreases. However, the method used to control leaving-tower water temperature to take advantage of this relationship is presently under debate.

For example, one study determined that the lowest possible leaving-tower water temperature is the "right" chiller plant operating point, but did so on the basis of data collected only at extreme conditions; that is, the tower was controlled to produce either the lowest water temperature possible or design temperature.[1]

> ...one utility realized that "low approach" chiller plant designs...can result in higher system consumption.

By the same token, at least one utility realized that "low approach" chiller plant designs with "inefficient" cooling towers could result in higher system, i.e., chiller plus tower, energy consumption. ("Approach" is the difference between the wet-bulb temperature and the leaving water temperature produced by the tower.) The utility subsequently implemented a cap on tower fan horsepower to assure that their incentive program for "low-approach" cooling towers effectively reduced total energy demand.[2]

Still others (Braun and Diderrich,[3] for example) state: "For a given set of conditions, an optimal tower control exists that minimizes the sum of the chiller and cooling tower fan power." Their peer-reviewed paper contends that neither maintaining a fixed tower water temperature nor a constant approach is optimal.

The simple evaluation method presented here for comparing chiller/tower energy consumption supports the claim that an "extreme" strategy (providing the coldest leaving-water temperature possible) is not optimal under all conditions. This method helps the designer to quickly examine the effect of leaving-tower water temperature on a particular chiller/tower pair. Armed with that knowledge, the designer can then decide whether to "take it to the limit…or just halfway."

The Evaluation Method

The concept is simple: one chiller is paired with one cooling tower and the flow of water between them remains constant. Certified selection programs supplied by the respective manufacturers predict chiller and cooling tower performance. A cooling tower selection program provided by the tower manufacturer is run at various load and ambient conditions, first with the fans operating at full speed, then at half speed.

Obviously, altering the tower fan speed will change the tower's leaving water temperature and, in turn, affect the chiller's power consumption. With the aid of the chiller and cooling tower selection programs, the chiller/tower pair's part-load energy consumption can be compared at high and low tower fan speeds.

The steps in this process follow:

1. Select a chiller at "normal" tower approach temperatures.[4]
2. Select a tower at these conditions. For the first iteration, select the low-cost cooling tower.[5]
3. For this chiller and tower combination, run the tower selections at half speed.
4. Perform Step 3 for part-load conditions down to 30%.
5. Using the same chiller, repeat steps 2, 3 and 4 for a "low horsepower" tower and a "very low horsepower" tower (quite often the most expensive alternative).
6. Repeat Steps 1 through 5 for approach temperatures down to 4°F (2.2°C) (or other selected limit).
7. Examine the trend and observe that fans running at part speed can often save "chiller plus tower" energy consumption. Tower fans with variable frequency drives are addressed later.

Demonstration of the Evaluation Method

The following example demonstrates this evaluation method.

Assumptions. The full-load design capacity of the example

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			High-Speed Tower Fan Data						Half-Speed Tower Fan Operation						Totals	
% Load	WB F	# Fans	ECWT F	Chil kW	Hp/ Fan	Eff	Twr kW	Sys kW	ECWT F	Chil kW	Hp/ Fan	Eff	Twr kW	Sys kW	kW Saved	% Saved
100	78	3	82.0	566	40	0.93	96	662	87.5	624	5.7	0.90	14	638	+24	+3.6
90	76	3	80.0	476	40	0.93	96	572	85.0	516	5.7	0.90	14	530	+42	+7.4
80	74	3	77.5	405	40	0.93	96	501	83.0	439	5.7	0.90	14	453	+48	+9.6
70	72	3	75.5	343	40	0.93	96	439	80.5	369	5.7	0.90	14	383	+56	+12.8
60	70	3	73.0	287	40	0.93	96	383	78.0	308	5.7	0.90	14	322	+61	+15.9
50	68	3	71.0	239	40	0.93	96	335	75.0	254	5.7	0.90	14	268	+67	+20.0
40	66	3	68.5	194	40	0.93	96	290	72.0	205	5.7	0.90	14	219	+71	+24.5
30	64	3	66.0	153	40	0.93	96	249	69.0	160	5.7	0.90	14	174	+75	+30.1

Table 1: Chiller/tower evaluation for power savings (Kansas City: 78°F wb, 4°F approach).

chiller/tower pair is 1,000 tons (3517 kW). Tower fan motor efficiency is 93% at high speed and 90% at half speed. Since the present "industry-average" chiller is based on 0.60-kW/ton performance at ARI Standard 550 rating conditions, the "base" chiller was selected at those parameters.

With one exception (noted later in this article), selections made at other condenser water temperatures permitted only impeller and motor changes to assure consistency at all examined conditions.

Evaluating A Single Design. *Table 1* summarizes the conditions evaluated in this example, as well as the resulting chiller-plus-tower performance. The first row of data identifies the design parameters:

• 78°F (25.5°C) wet-bulb temperature (0.4% design wet-bulb temperature in Kansas City, Mo. per *1997 ASHRAE Handbook—Fundamentals*).

• 4°F (2.2°C) approach temperature (82°F [27.7°C] entering condenser water temperature [ECWT])

• Low-cost tower selection

Other data provided in *Table 1*, by column, includes:

• **%Load:** Percent of full-load capacity.

• **WB:** Ambient wet-bulb temperature (°F) at a particular load.

• **# Fans:** Number of cooling tower fans.

• **ECWT:** Water temperature (°F) entering the chiller's condenser with tower fans operating at high- and half-speed, respectively. It is assumed to be the same as the water temperature leaving the tower and was provided by the cooling tower selection program.

• **Chil kW:** Power (kW) drawn by the chiller at this load and ECWT per the chiller selection program, with the tower fans operating at high- and half-speed, respectively.

• **Hp/Fan:** Horsepower (hp) of each cooling tower fan with the tower fans operating at high- and half-speed, respectively; provided by the cooling tower selection program.

• **Eff:** Fan motor efficiency cataloged by the cooling tower manufacturer with the tower fans operating at high- and half-speed, respectively.

• **Twr kW:** Power (kW) consumed by the tower with the

Selection Criteria	No. of Fans	Hp/Fan	Hp/Ton
Low Cost (LoCost)	3	40	0.12
Low Horsepower (LoHp)	3	30	0.09
Very Low Horsepower (VLoHp)	2	30	0.06

Table 2: Tower selections for 78°F wb and 4°F approach design temperatures.

tower fans operating at high- and half-speed, respectively (i.e., # Fans · Hp/Fan · 0.746 (kW/hp) ÷ Eff).

• **Sys kW –** Chil kW + Twr kW, with the tower fans operating at high- and half-speed, respectively.

• **kW Saved:** High-Speed Sys kW – Half-Speed Sys kW.

• **% Saved:** kW Saved ÷ High-Speed Sys kW.

Positive values in the **Total kW Saved** and **Total % Saved** indicate that the chiller/tower pair consumes less energy when the tower fans run at half speed. Conversely, if less power is required when the fans operate at high speed, negative values will appear in these columns.

Before we examine *Table 1* more closely, it is important to note that a chiller selected to provide 1,000 tons (3517 kW) at 82°F (27.7°C) ECWT (high-speed fan operation) will fall short of this capacity when the ECWT is 87.5°F (30.8°C) (half-speed fan operation). Therefore, at full-load conditions only, the chiller's impeller and motor were reselected to satisfy a 100% load at the elevated ECWT.

While *Table 1* does not represent all chiller/tower designs, it does illustrate several interesting points. For example, a comparison of the **Sys kW** columns reveals that the low-approach, low-cost tower in this system design consistently results in lower system energy consumption when the tower fans run at half speed (e.g., 638 kW at 100% load) than at high-speed (e.g., 662 kW at 100% load).

Now compare the values in the **Chil kW** columns. Once again, the results are consistent. This time, however, running the tower fans at high speed apparently yields the lowest en-

			High-Speed Tower Fan Data						Half-Speed Tower Fan Operation						Totals	
% Load	WB F	# Fans	ECWT F	Chil kW	Hp/ Fan	Eff	Twr kW	Sys kW	ECWT F	Chil kW	Hp/ Fan	Eff	Twr kW	Sys kW	kW Saved	% Saved
100	71.0	2	80.0	544	40	0.93	64	608	89.0	639	5.7	0.90	9	648	40	6.6
90	69.6	2	78.0	455	40	0.93	64	519	87.0	530	5.7	0.90	9	539	20	3.9
80	68.2	2	76.0	389	40	0.93	64	453	84.5	444	5.7	0.90	9	453	0	0.1
70	66.8	2	74.0	329	40	0.93	64	393	82.0	371	5.7	0.90	9	380	+13	+3.2
60	65.4	2	72.0	276	40	0.93	64	340	79.0	307	5.7	0.90	9	316	+24	+7.0
50	64.0	2	70.0	230	40	0.93	64	294	76.0	252	5.7	0.90	9	261	+33	+11.1
40	62.6	2	67.5	186	40	0.93	64	250	73.0	203	5.7	0.90	9	212	+38	+15.1
30	61.1	2	65.0	146	40	0.93	64	210	69.5	157	5.7	0.90	9	166	+44	+20.8

***Table 3:** Chiller/tower evaluation for power savings (Long Beach: 71°F wb, 9°F approach).*

			High-Speed Tower Fan Data						Half-Speed Tower Fan Operation						Totals	
% Load	WB F	# Fans	ECWT F	Chil kW	Hp/ Fan	Eff	Twr kW	Sys kW	ECWT F	Chil kW	Hp/ Fan	Eff	Twr kW	Sys kW	kW Saved	% Saved
100	66.0	2	76.0	508	40	0.93	64	572	86.0	608	5.7	0.90	9	617	45	7.9
90	64.2	2	73.5	417	40	0.93	64	481	83.5	494	5.7	0.90	9	502	22	4.6
80	63.0	2	72.0	358	40	0.93	64	422	81.0	412	5.7	0.90	9	421	1	+0.2
70	61.6	2	70.0	302	40	0.93	64	366	78.5	344	5.7	0.90	9	353	+13	+3.5
60	60.0	2	67.5	249	40	0.93	64	313	75.5	282	5.7	0.90	9	291	+22	+6.9
50	59.0	2	65.5	203	40	0.93	64	267	73.0	231	5.7	0.90	9	240	+27	+10.0
40	58.1	2	63.5	165	40	0.93	64	229	69.5	183	5.7	0.90	9	192	+37	+16.0
30	56.7	2	61.0	130	40	0.93	64	194	66.0	141	5.7	0.90	9	150	+44	+22.6

***Table 4:** Chiller/tower evaluation for power savings (Salt Lake City: 66°F wb, 10°F approach).*

ergy consumption. If the tower control strategy was based on chiller performance alone, the conclusion would be that it does not make good economic sense to run the tower fans at anything less than high (full) speed.

Together, these comparisons demonstrate that tower fan energy consumption should not be disregarded in the effort to achieve low-approach design temperatures. While this conclusion may seem extreme, it is what prompted the utility discussed earlier to qualify fan horsepower in its incentive program for low-approach cooling towers.

Identifying Trends. This evaluation method gives designers a simplified look at the effect of a specific chiller/tower control strategy. By selecting several cooling towers for a particular approach temperature, the same method can be used to identify trends. *Table 2* summarizes three sample cooling tower selections chosen to provide "low (first) cost," "low horsepower" and "very low horsepower."

Approach temperatures of 4°F (2.2°C), 5°F (2.7°C), 6°F (3.3°C) and 7°F (3.8°C) at a design ambient wet-bulb temperature of 78°F (27.7°C) become ECWTs of 82°F (27.7°C), 83°F (28.3°C), 84°F (28.8°C) and 85°F (29.4°C), respectively. Low-cost, low-horsepower and very-low-horsepower towers were selected then for each design ECWT. Finally, the evaluation method introduced earlier was used for each part-load operating point.

It should be noted that an approach temperature of 4°F (2.2°C) can result in an "oversized" cooling tower. The examination of economics for such a cooling tower is not presented here. This article addresses the interaction between the cooling tower running at various speeds and the chiller.

Figure 1 illustrates the projected power savings (kW Saved ÷ High-Speed Sys kW) of half- versus high-speed tower fan operation. The top line, denoted as 82LoCost, represents the **% Saved** column in *Table 1* (i.e., 4°F [2.2°C] approach = 82°F ECWT [27.7°C]). Other tower selections are similarly identified.

Three trends immediately become apparent when the selection results are plotted in this manner:

• In all cases, savings achieved by running the tower fans at half speed increases as the chiller load decreases.

• At 50% load, all tower chiller configurations examined consume less power (**Sys kW**) when the tower fans run at half speed.

• At 30% load, even using the lowest horsepower fans selected (VLoHp), power savings of at least 7% can be achieved. And maximum savings in excess of 30% are possible.

What About Drier Climates? The trends graphed in *Figure 1* reflect Kansas City's 0.4% design wet-bulb temperature. To determine their validity for other weather locations, two other climates were considered:

• **71°F (21.6°C) wb,** Long Beach's 0.4% design wet-bulb temperature per *ASHRAE Handbook—Fundamentals*, at approach temperatures ranging from 4°F (2.2°C) to 9°F (5.0°C). As an example, *Table 3* gives data for a 9°F (5.0°C) approach using the low-cost tower.

• **66°F (18.8°C) wb,** Salt Lake City's 0.4% design wet-bulb temperature per *ASHRAE Handbook—Fundamentals*, at approach temperatures ranging from 4°F (2.2°C) to 10°F (5.5°C). As an example, *Table 4* gives data for a 10°F (5.5°C) approach using the low-cost tower.

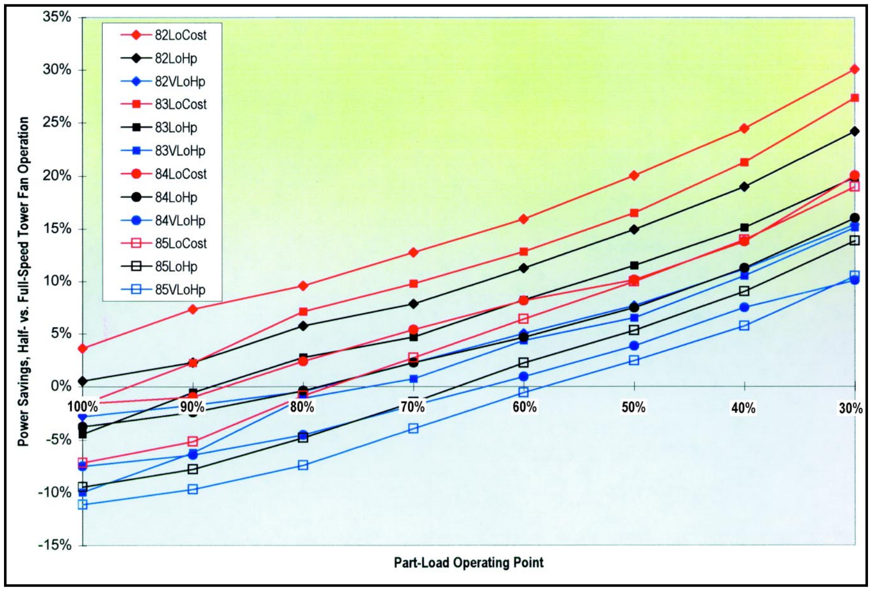

***Figure 1:** 78°F design wet bulb (Kansas City, Mo.).*

Figures 2 and *3* plot the results of these evaluations. While the slopes vary from *Figure 1*, the trends are clearly the same. At part-load operating points of 50% and less, in every case, this demonstrates that running the tower fans at half speed reduces total (chiller-plus-tower) energy consumption. Further examination may show that running the cooling tower fans at 70% or 80% of full speed (rather than at half-speed) saves even more power at part-load conditions.

What about using a cooling tower with variable frequency drives? The cooling tower selection programs presently available do not give selections for towers with a variable frequency drive. Therefore, the method presented here only examines tower fan operation at full and half speed. Half speed may not be the optimal condition in many applications.

Nevertheless, the method presented in this article can lead designers to quickly examine system operation at various conditions. Thus, less experienced designers can understand the system benefits of changing tower fan speed. It also gives the experienced designer a method to quickly examine systems at conditions with which the designer is not as familiar.

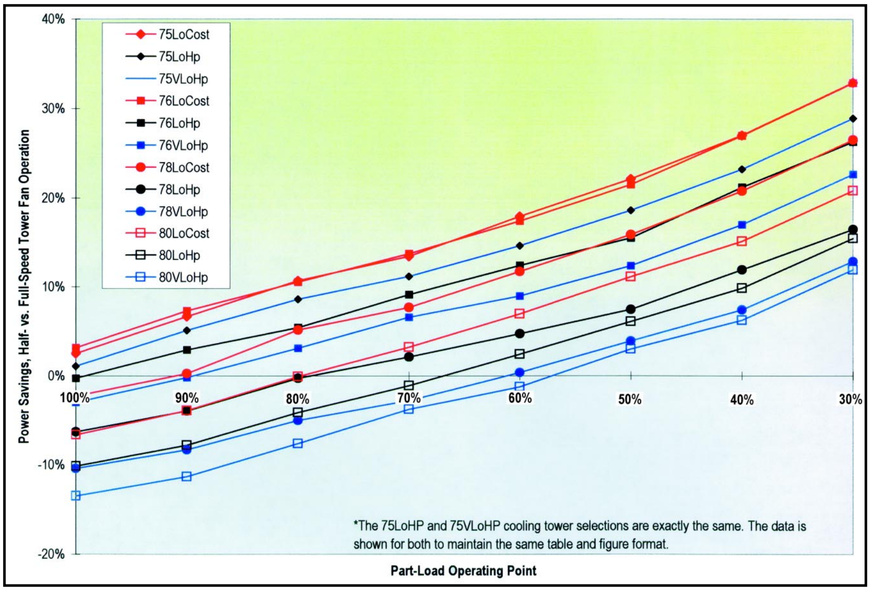

Figure 2: 71°F design wet bulb (Long Beach, Calif.).

For a more exhaustive analysis, there are a number of tools (both public domain and privately funded) that can be used to examine the economic justification for system components such as variable frequency drives on tower fans.

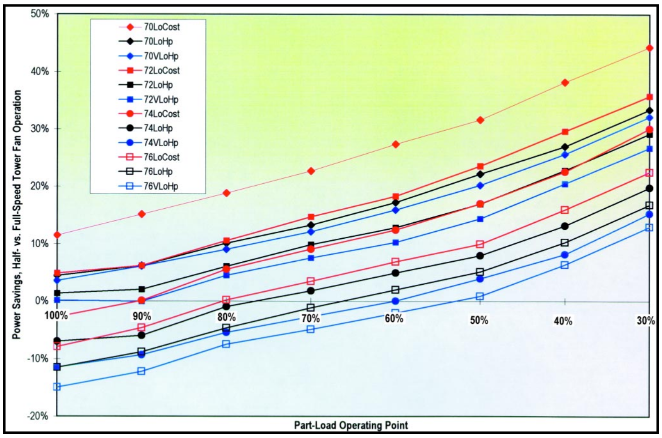

Figure 3: 66°F design wet bulb (Salt Lake City).

Conclusions

While this simple evaluation method is not exhaustive, it certainly reveals trends in chiller-plus-tower energy requirements at various loads. The validity of these trends for a chiller/tower system project can easily be checked using data provided by the equipment manufacturers.

The examples presented here demonstrate that systems with low-approach cooling towers must be designed with particular care. Choosing a tower with high-horsepower fans may defeat the power-saving intent of the tower's low-approach design.To determine whether this is the case, ask the cooling tower manufacturer for the leaving-tower water temperature with the fan(s) operating at half speed; then select a chiller with an entering condenser water temperature as close to that value as possible.

If the total energy consumption of the chiller/tower pair is less when the tower fans run at half-speed, the design does not make sense. Stated simply: the lowest possible leaving tower water temperature does not always conserve system energy. Do not ignore the cooling tower's power consumption at any part load condition. Depending on design parameters, significant savings may be obtained at part load, especially at operating points below 50% of full load.

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